IMPROVED FIELD EMITTER CURRENT DENSITIES AND STABILITY THROUGH THE APPLICATION OF A PROPRIETARY PROCESS

CONTRACT MDA972-92-C-0033
QUARTERLY REPORT #2 June-August '92

I. INTRODUCTION

This brief report highlights the technical progress made during the three-month period covered on the contract. The contract goals are to demonstrate a three-terminal vacuum microelectronic device having a current gain cutoff frequency f_t of at least one GHz at a current density of at least 5 A/cm^2, stable over a period of 2 hours or more.

The previous report described the advantages of the single-crystal approach being employed for the contract. Linear current densities of 0.8 mA/mm were reported, within a factor of 3 needed to theoretically satisfy the performance goals of the contract (Task 1 of the SOW). Furthermore, these current densities were realized in conventional 10^{-6} Torr vacuum levels without a UHV bake out as is necessary for non crystalline structures. The current emission would remain stable over a period in excess of several days.

During this period the focus was on improving the linear current density to the value needed to achieve $f_t \geq 1$ GHz. To better communicate the impact of the work done during the period, the results are presented first, followed by the experimental work behind these results.

II. CURRENT DENSITY IMPROVEMENT

During this period the linear current density was improved from ~ 0.8 mA/mm to ~3 mA/mm. Since theoretically the capacitance per unit length of a emitter-gap of 0.5 micron is .03 pF/mm, and with g_m =12.44 I/V, then for V=150 V, $f_t = g_m/(2\pi\ C)$ requires I $\equiv$ 2.4 mA/mm for f_t = 1 GHz.

By using a new surface treatment (detailed in the next section), the current density was improved to 0.8 mA/250 μm (Fig.1), or equivalently 3.2 mA/mm. These values were obtained in conventional 10^{-6} Torr vacuum levels without any bakeout. Devices without the improved surface treatment were baked at 250°C in UHV for 48 hours and achieved 2.6 mA/mm. The implication is that the improved surface treatment coupled with the UHV bakeout would achieve even higher levels of current. However, such is not likely to be the case since both the UHV and the surface treated devices appeared to be limited by substrate breakdown. A deeper well etch and/or a thicker AlGaAs buffer layer would improve the breakdown voltage, but the resulting large overhang would press the limits of fragility that are currently being approached (Fig.2) At present, it is not felt that the breakdown voltage needs to be raised since the desire current levels have been achieved. If needed, the breakdown voltage could be improved by possibly introducing more traps in the AlGaAs, or by thickening the n+ emitter-gate layer from 1000Å to, say, 2000Å to enable a deeper well to be etched.

Summarizing, the emission current levels needed for one GHz operation have been achieved For a five micron finger width, these linear current densities translate into an area current density of 60 A/cm^2, well in excess of the contract requirement.

III. Experimental Work to Improve Emission

The following text describes briefly actions taken to improve the linear current density, either by lowering the threshold or by optimizing the surface conditions.

A. <u>Brief Experiments</u>: An effort to lower the voltage threshold by narrowing the E-beam exposure that defines the emitter-gate gap was repeated. However, the reduction in the resist opening from 0.35 um to 0.1-0.15 um succeeded only in reducing the emitter-gate gap from 0.5 to 0.4-0.45um. Although the top of the resist opening may reflect the desired width reduction, the etched results seem to indicate that the base of the resist for the two exposures are not very different. This small change in emitter-gate separation did not significantly increase the gap between emission threshold and substrate breakdown.

Devices that have been thinned and scribed always need a 5/5 sec. ammonia/HF etch to restore emission.

To test how well the HF was passivating the GaAs surface (as with Si, fluoridation of the surface bonds retards oxidation), a comparison between a 5 and a 60 second HF treatment was done. It is desired to keep the time to a minimum since the HF also etches the AlGaAs well, increasing the electrode overhangs (Fig.2). After bonding (which involves heating in air) no emission threshold difference could be detected, suggesting complete fluoridation after 5 sec.

Heating the devices in conventional vacuum with a quartz IR lamp did not imprve emission.

An SEM comparison of devices which easily emitted with those who did so with difficulty showed no differences in edge roughness or protrusion spikes.

B. <u>Another Advantage for GaAs</u>: The following describes an experiment that seems to suggest a very low oxidation rate for GaAs. An old run which had been sitting in room air for about 6 months was found to emit as easily as it did 6 months ago. An HF etch to remove any existing oxide did not change the emission. The conclusion reached was that GaAs oxidizes very slowly, or the original HF passivation works very well, or both. Fig. 3 taken from Ref. [2] suggests the former, indicating that it take four orders of magnitude increase in oxygen exposure (either level or time) to produce the same effect as for silicon. Indeed, silicon emitters, after sitting in room air for a few days, would not emit until the voltage exceeded that of the original threshold by some tens of volts, after which the emitter would "pop" back to it original emission characteristic.

Thus, besides the availability of an insultating substrate (for frequency performance) and the ability to grow hetero epitaxial materials (to achieve the Fig. 2 structure), a passive surface adds to the advantages that GaAs has over silicon for vacuum microelectronic applications.

C. Improved Surface Treatment: Ref. [3] indicates that instead of fluoridating the GaAs surface, HF passivates the surface with a 20 Å layer of As. Feeling that the As will not only provide a barrier to electron emission, but could also be ejected from the surface and precipiate an arc, the final etch was changed to an ammonia etch. An immediate improvement was seen as the maximum current improved by a little less than an order of magnitude to that shown in Fig.1.

This surface passivation procedure change was the most important accomplishment during this period. The current limiting mechanism now appears to be the substrate breakdown voltage, an issue that need not be attacked for now since, as discussed in Section II, the current density level appears sufficient for one GHz operation.

IV Emission Uniformity Test

An interesting phenomenon was discovered when operating the tips at atmospheric pressure. Instead of electrons, the emitter would emit OH^- or possibly CO_3^- ions and sputter the gate away after ~ 1 minute of operation. The color changes of the gate as it was thinned could be observed directly under the microscope while in operation. Besides the interesting possibility of a "micro" sputtering source, this mode of operation may offer an easy method to test for electron emission uniformity. Although uniformity in electron emission may not follow from uniformity in ion emission, the converse is probably true with the regard to non uniformity (e.g., non uniform ion emission implies the electron emission will be non uniform). For most of the device runs the color change on the gate was typically uniform, and for cases for which it was not, a light dilute ammonia etch (~ 5 sec) usually resulted in uniformity.

V CONTRACT SUMMARY

The current density has been improved to the desired value needed for one GHz operation. So far there are no area of concern. Plans for the next quarter are to simulate electron trajectories upon which to base the mask designs for the microwave studies.

REFERENCES

1. C. A. Spindt, I. Brodie, L. Humphrey and E. R. Westerberg, "Physical Properties of Thin Film Emission Cathodes with Molybdenum Cones", J. Appl. Phys. 47, 5248 (1976).
2. P.Mark and W.F. Creighton, "Chemical Trends in Oxygen Uptake...", Appl. Phys. Lett. 27, 400 (1975).
3. K. Menda, E. Kanda and T.Yokoyama" ARXPS Analysis on As-Passivated GaAs Surfaces by HF Dipping Method", Jap. J. Appl. Phys. 29 L39 (1990)

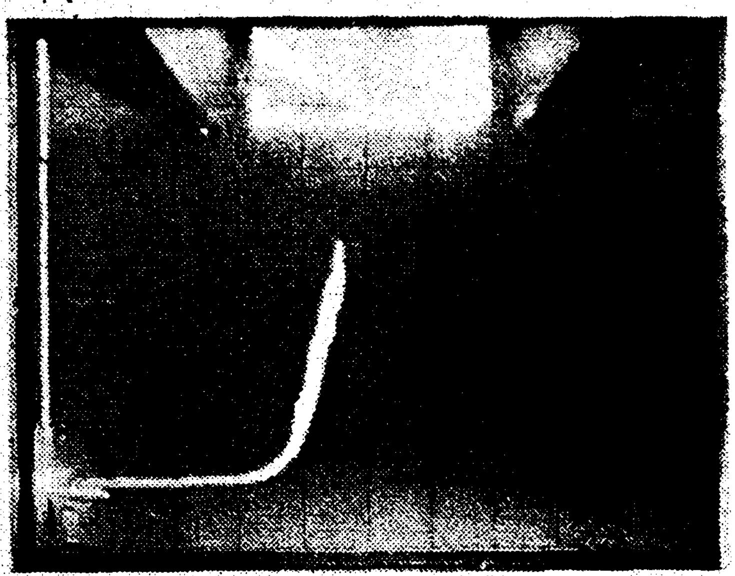

Fig. 1 3mA/mm linear current density (0.2mA, 50V/Div)

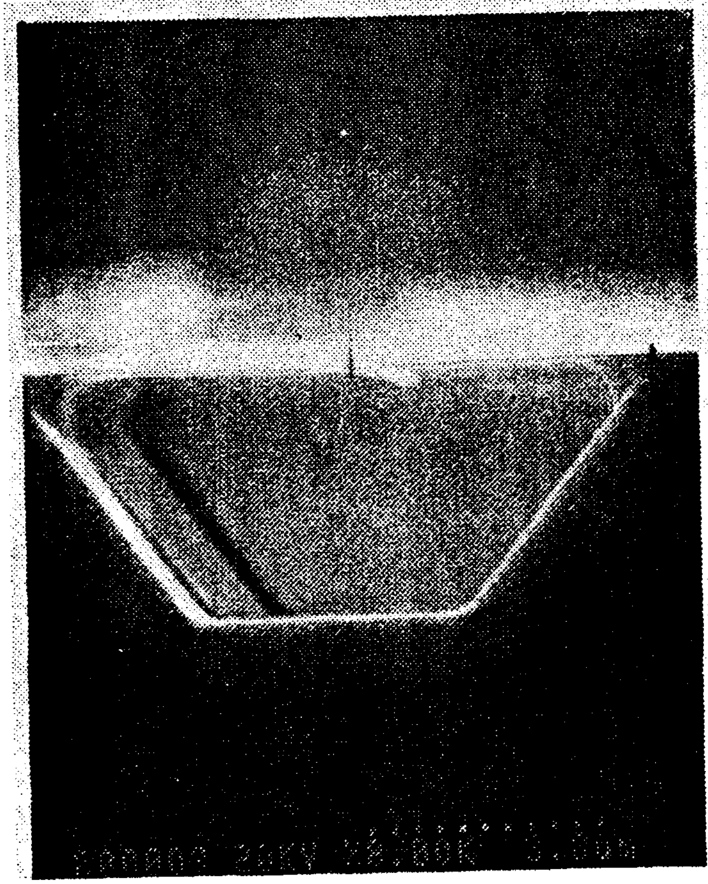

Fig. 2 Emitter-gate electrode overhangs

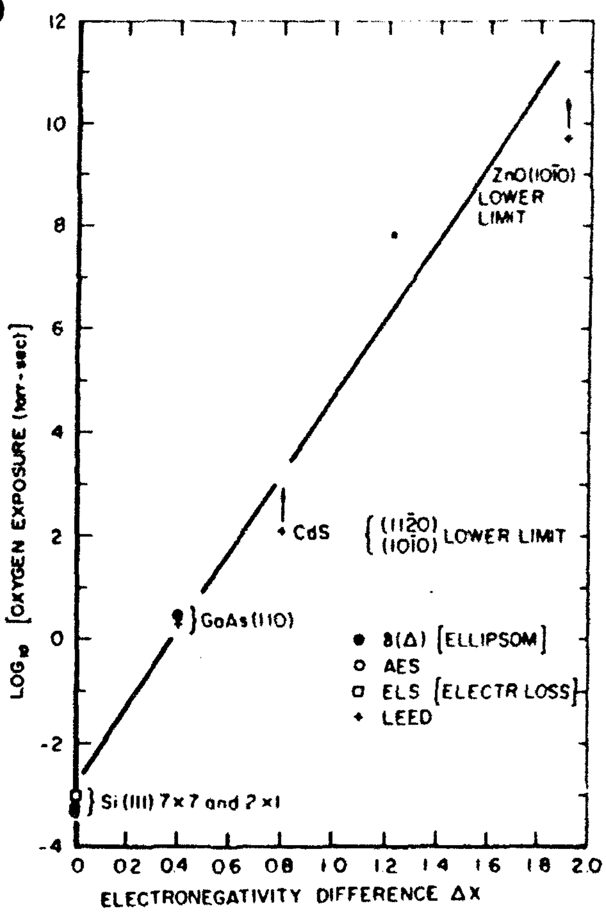

Fig.3 Comparison of GaAs and Si for sensitivity to oxidation